RATE OF GLACIAL VALLEY DEEPENING DURING THE LATE QUATERNARY IN ASSYNT, SCOTLAND

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ABSTRACT

A dated landscape history of the Allt nan Uamh valley in the Assynt area is constructed, spanning the last 300 ka, using geomorphological analysis, U-series speleothem dating, and existing cave surveys. The mean rate of valley deepening is estimated to lie between 47 and 68 m per glacial/interglacial cycle of 100 ka. This, combined with an estimated duration of glaciation, implies glacial erosion rates of about 2 mm a^{-1}, in agreement with modern process measurements. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The landscape of the Scottish Highlands has been shaped by repeated episodes of glacial erosion. However, terrestrial evidence for the number of Quaternary glaciations in Scotland and for their timing, extent and individual impacts is very limited because of their destructive nature. Scant depositional evidence of events before the last (Late Devensian) glaciation survives in Scotland (Boulton *et al*., 1991). Offshore deposits can be interpreted as consisting largely of the transported sediments produced by earlier glaciations, but their stratigraphy is not precise enough to deduce the number or timing of such events (Clayton, 1996). Thus, although glacial landforms themselves bear witness to the cumulative effects of glacial erosion, the overall time-scale involved in producing them is still uncertain, as is the duration of the actual periods of glaciation and the rates of erosion that they accomplished.

One method of resolving this conundrum is to identify a dated reference level or surface in the landscape itself, from which the impact of later erosion can be measured. In this study we use karst caves in the Assynt district in NW Scotland (Figure 1), which have been dissected by a glaciated valley, to provide such a reference. Time control provided by U-series dates on speleothems allows an estimate of the local rate of valley floor deepening during the last 300 ka.

THE STUDY AREA

The part of Assynt studied straddles two major units of geological structures produced in the Caledonian orogeny (Figure 1). To the west of the Sole Thrust lies a foreland of Lewisian Gneiss overlain by Torridonian Sandstone and Cambrian quartzites. To the east is the structurally complex Moine Thrust Belt, in which slices of Lewisian, Torridonian and Cambro-Ordovician rocks have been transported westwards on a series of thrust planes (Johnson and Parsons, 1979).

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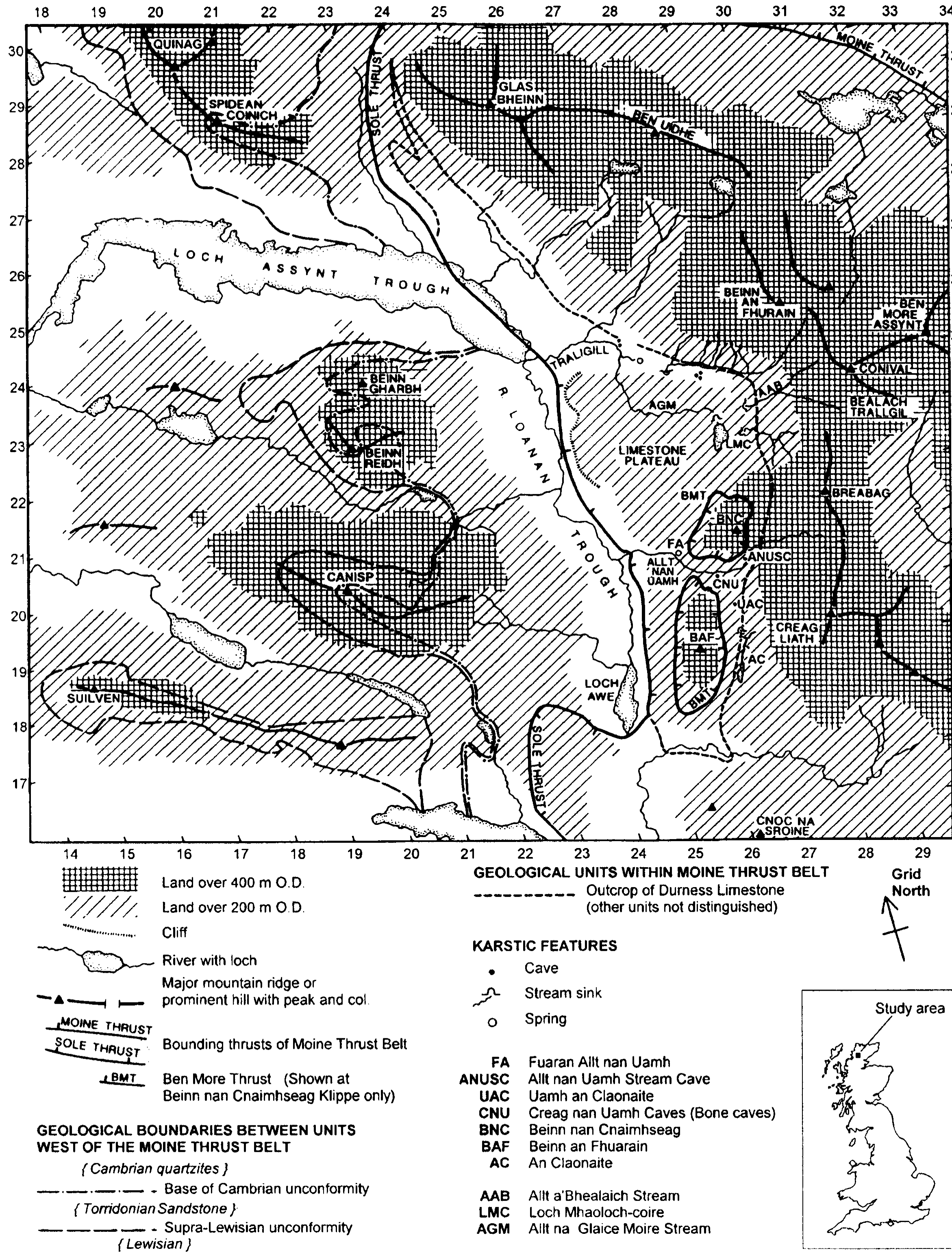

Figure 1. Major geomorphic and geological features of the Assynt area.

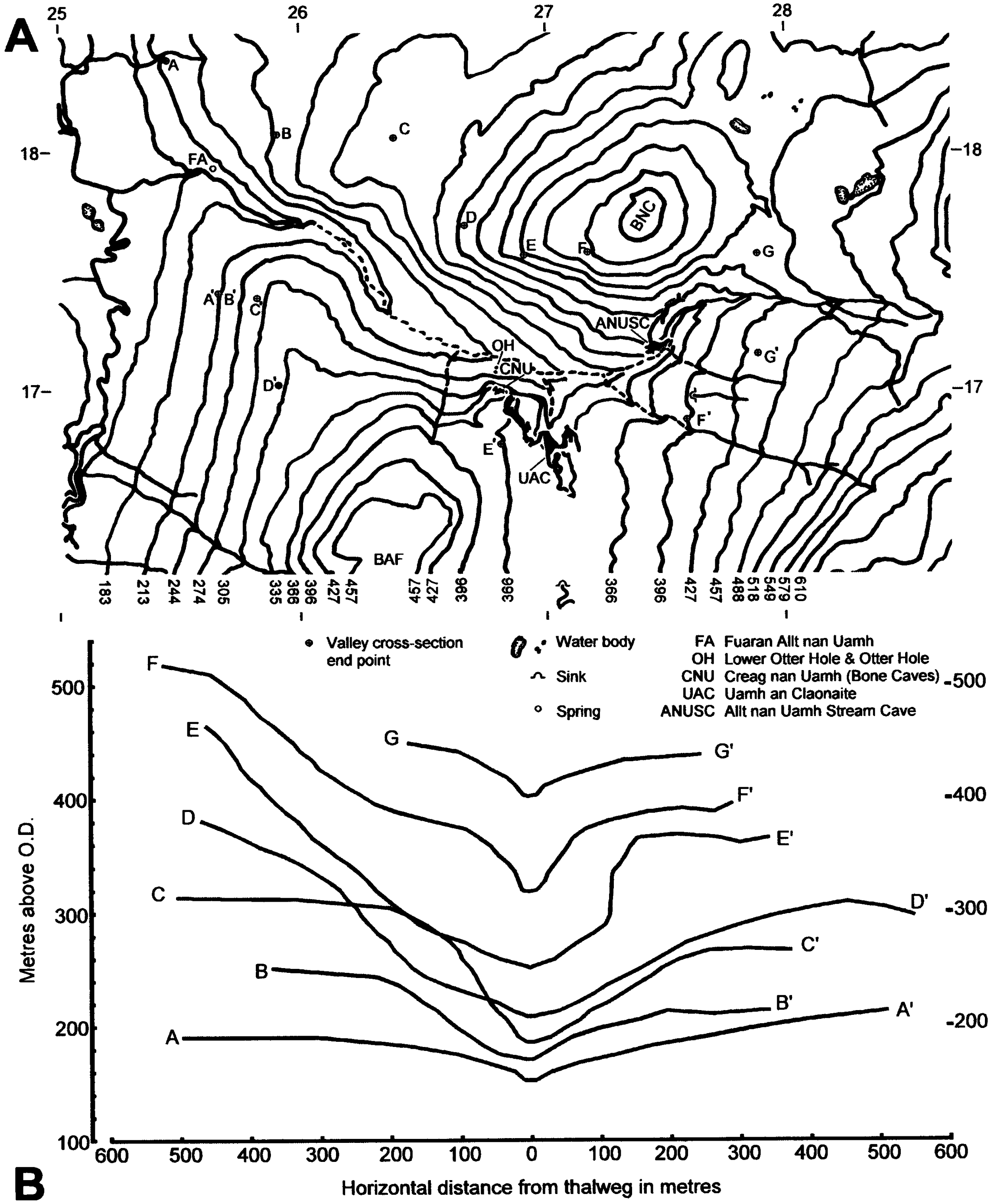

Figure 2. (A) Contour map of the Allt nan Uamh valley showing cross-section locations. Permanent streams are shown as continuous lines; ephemeral water courses (from which water is diverted into the karst system) are shown as broken lines. (B) Cross-sections illustrating the valley's glaciated form.

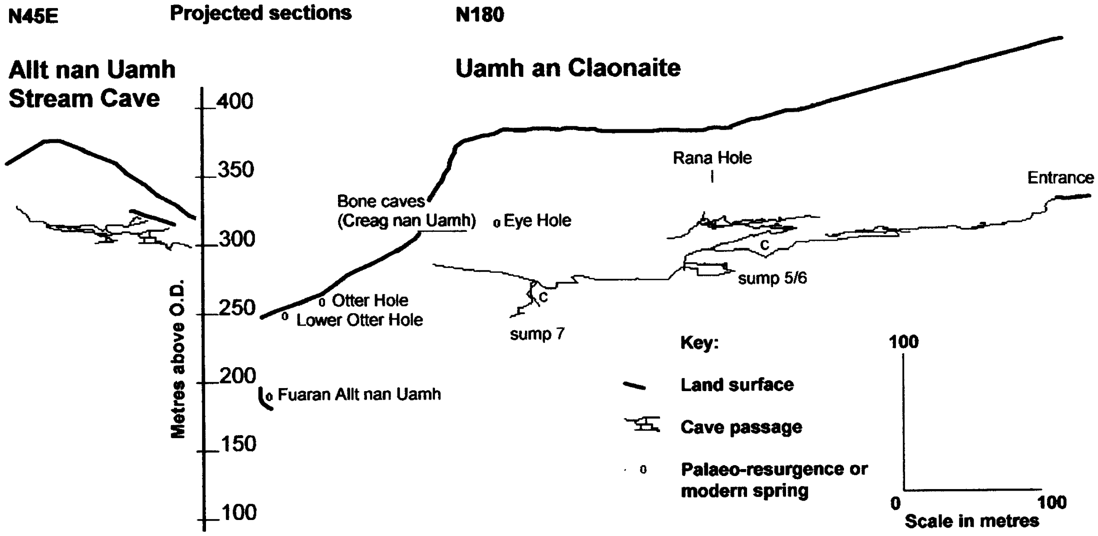

Figure 3. Projected elevations of major caves in the Allt nan Uamh basin. Underground capture points are marked 'C'.

The eastern extent of the study area is delineated by the mountain ridges that form the present Atlantic/North Sea drainage divide. In the west, a belt of high ground is formed by quartzite-capped hills of Torridonian Sandstone resting on the Lewisian basement. Aligned north–south between these two uplands, the Loanan valley is a glacially eroded trough formed along the strike of the Sole Thrust. At Inchnadamph, the long axis of the Loanan trough turns through *c*. 50° and passes through the western belt of hills via a major glacial trough, overdeepened by 80 m and now occupied by Loch Assynt. Immediately east of the Loanan–Assynt trough lies a pocket of glaciokarst developed on the Cambro-Ordovician Durness Limestone. These dolomitic limestones form a plateau 1–4 km broad which has been incised by valleys draining westwards from the watershed hills towards the Atlantic. The two major valleys are those of the River Traligill and Allt nan Uamh ('Stream of the Caves'); both show unmistakable signs of glacial excavation (Figure 2). A cliffed scarp defines the western limit of the limestone plateau along the Loanan trough between the mouth of the Traligill basin in the north and the Allt nan Uamh basin to the south.

Evidence of erratics (Lawson, 1983, 1995a) indicates that the ice divide of the last ice sheet, and presumably that of previous glaciations, lay to the east of the present watershed. Striations, crescentic cracks and trains of erratics all show that regional ice flow was westward once the ice mass had grown sufficiently large to overtop the drainage divide, with topography exerting only a local influence on flow direction. This suggests that the Loanan trough lay across the ice flow direction and would have been less susceptible to deepening by westward-flowing ice whereas the east–west trending Loch Assynt trough should have experienced the greatest amount of erosion. This is indeed the actual pattern of relief. The Traligill and Allt nan Uamh valleys, being aligned roughly parallel with ice sheet flow, were probably also eroded effectively during the maximal state of glaciation. It has been suggested (Lawson, 1990; Lawson and Ballantyne, 1995) that during ice sheet build-up the style of glaciation would have been different, involving corrie and valley glaciers. Although direct evidence survives only of corrie glaciers which were active during the Loch Lomond Stadial (Younger Dryas), the hypothesized state of widespread valley glaciation during ice sheet build-up and decay would have caused erosion and deepening of all the principal valleys, regardless of alignment.

The hydrology and underground drainage of the limestone plateau basins has been strongly controlled by the tectonic structures of the thrust belt. At present the basins are drained largely underground via karst caves. Much of the limestone plateau surface is relatively intact, having been preserved from fluvial dissection by diversion of drainage underground and by glacial erosion having been focused along the main valleys of Traligill and Allt nan Uamh.

A sequence of base-level lowering events is recorded by the altitudinal stratification of cave passages (Figure 3). This evidence, coupled with a model of the development of cave systems and the dating of some of their interior deposits, can be used to reconstruct parts of the environmental and surface lowering history of the neighbouring valleys. Such a history is presented in outline for the Allt nan Uamh valley.

ESTIMATION OF BASE-LEVEL LOWERING RATE

Altitudinal stratification of the Allt nan Uamh caves

The principles of cave genesis and the relationships between passage form and origin are reviewed by Ford and Williams (1989, Ch. 7) and their applications to landscape evolution are described by Atkinson and Rowe (1992). In brief, the geometry and morphology of groups of fossil cave passages provide evidence of palaeowater-table altitudes. Passages formed beneath the water table tend to have up-and-down profiles and tubular cross-sections, sometimes modified to a more rectangular form by roof collapse. They are known as ‘phreatic tubes’. In contrast, passages above the water table have slot-like cross-sections resulting from cave streams eroding downwards into their floors, and profiles sloping consistently downstream. They are known as ‘vadose canyons’. Composite, keyhole-shaped cross-sections can result from the enlargement of formerly phreatic passages.

The highest levels of the known caves in Allt nan Uamh (Ford, 1959; Lawson, 1988) consist of a complex of large abandoned phreatic tubes, part-filled with sediment (Figure 3). They represent the earliest surviving evidence of cave development, indicating a contemporaneous water table at or slightly above 330–340 m OD, denoted Stage A on Figure 4. The modern valley is cut far below them and in several places truncates the cave galleries, most obviously at the Bone Caves (Figure 3). Younger and almost invariably smaller phreatic passages are exposed by truncation at lower levels. No direct evidence of the exact location of palaeoresurgences has survived because of subsequent valley deepening. However, repeated downward shifts in spring position are recorded by the altitudes of constricted cave passages at Otter Hole (Stage B) and Lower Otter Hole (Stage C) (see Figures 3 and 4), and by clear morphological evidence of underground stream capture at two levels in Uamh an Claonaite (Figure 3). Fuaran Allt nan Uamh, the present main resurgence (Stage D), is at 190 m OD. The diminution of passage size towards lower altitudes implies that the younger passages had less time for enlargement before further valley deepening and consequent base-level lowering occurred. The pattern of vadose entrenchments and passage linkage seen at the points labelled ‘C’ in Figure 3 demonstrates underground drainage capture in response to episodic changes in base-level. These are tentatively assigned to valley deepening by consecutive glaciations.

The duration for which phreatic conditions were maintained above the Stage A passages is not known. However, their large diameter relative to the later passages suggests that their enlargement continued over more than one glacial/interglacial cycle. A structural factor which may possibly have contributed to the maintenance of phreatic conditions is shown on Figure 4. The Allt nan Uamh cuts through a structurally inverted klippe of Torridonian Sandstone which forms local hilltops on either side of the valley (‘BNC’ and ‘BAF’ on Figure 1). The klippe rests on the Ben More Thrust which dips *westward* at this point, bringing the base of the klippe to altitudes almost coincident with the Stage A palaeowater-table, or below it (Figure 4). It is highly likely that the surviving outcrops of Torridonian Sandstone once formed the opposite ends of a now-breached aquitard. It is probable that the Stage A passages were formed when groundwater in the limestones was dammed by this aquitard and flowed towards a resurgence on the up-valley side of the barrier. No trace exists of mature cave passages at any level in the valley, downstream of the lowest klippe outcrop. It seems likely that the downstream diversion of underground drainage from Stage A to Stage B became possible only once incision of the Loanan and the lower Allt nan Uamh valleys had fully breached the Torridonian klippe.

Establishing a chronology and average rate for base-level lowering

On the basis of the morphological evidence, incision of the Allt nan Uamh has diverted the underground drainage to deeper base-levels at least three times. An overall time-scale can be put on these events by the results of U-series dating of speleothems. A programme of sampling and comprehensive dating of speleothems

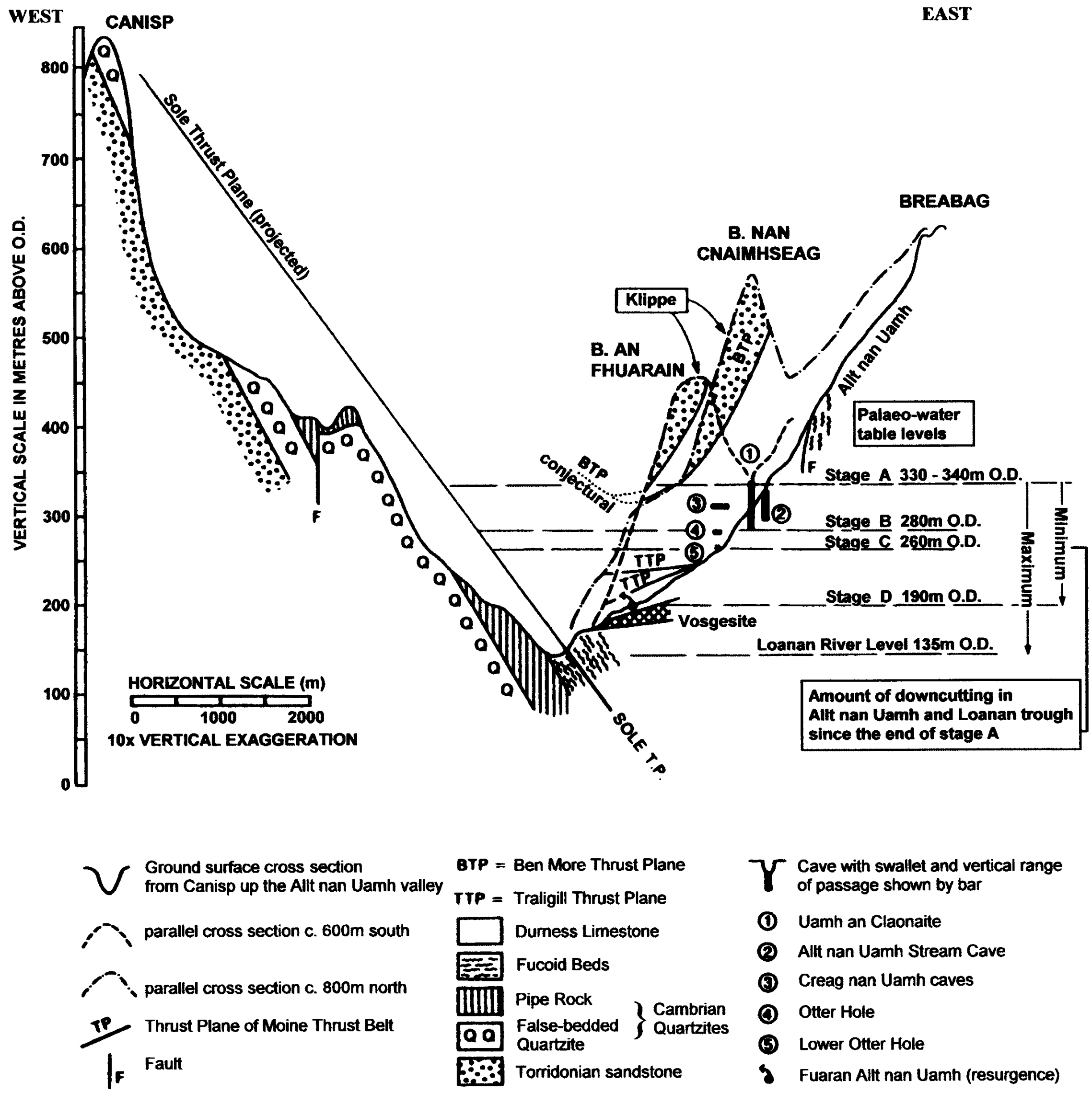

Figure 4. Cross-section from the Torridonian Sandstone hills along the Allt nan Uamh valley, showing the relationship between modern topography, geological structure, glacial excavation and the cave passage altitudes and palaeowater-levels.

is in progress, and completed results for the Allt nan Uamh are shown in Figure 5. All of the speleothems were formed by dripping water in air-filled cavities, and all came from Stage A phreatic tube passages. Therefore, the base-level diversion from Stage A to Stage B must have been brought about *before* the deposition of the oldest speleothems. These are flowstones deposited around 200 ka (Figure 5), contemporaneously with the interglacial Oxygen Isotope Stage (OIS) 7 of the ocean Quaternary time-scale. Since base-level diversion was apparently episodic, it is attributed to a period of rapid glacial deepening of the valley. This glacial erosion cannot feasibly have occurred later than OIS 8 (*c*. 280 ka). It might conceivably have been earlier, perhaps in OIS 10 or 12, both glacial stages in which ice sheet glaciation of Scotland might be expected to have occurred. An earlier date would imply that any speleothems deposited before OIS 7 have been destroyed or made inaccessible through burial by later sediments. Placing the Stage A/B transition in OIS 8 or before implies that the caves underwent

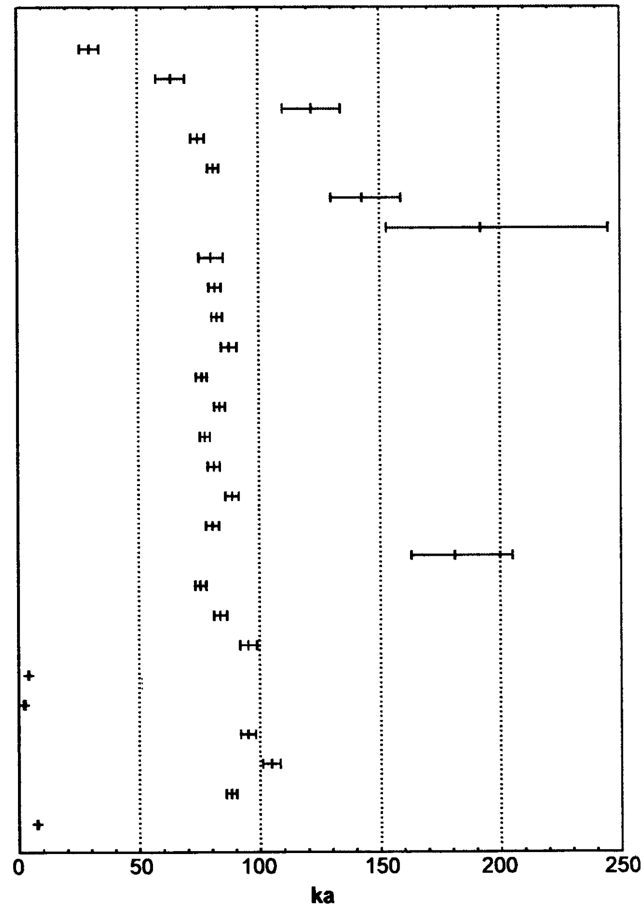

Figure 5. Uranium-series dates from the Allt nan Uamh basin with 1-σ error bars. Full data are in Lawson and Atkinson (1995). Detrital contamination is negligible.

several further episodes of glaciation in the time elapsed since. This would account for the several episodes of base-level diversion observed. Confirmation of this comes from the fact that the caves contain glacially derived sediments. These are described by Lawson (1995b,c) and Atkinson *et al*. (1995), who demonstrate that they consist of two main facies originating from outside the caves, plus speleothems and roof breakdown blocks derived from within the passages themselves. The two allochthonous facies are silts and fine sands deposited under low energy conditions while the passages were completely water-filled, and coarse sands, gravels and boulders reworked from tills and deposited by very high energy, invading, vadose streams. The silt facies were deposited in subglacial conditions when the caves were water-filled and flow velocities were controlled by englacial hydraulic gradients (*cf.* Schroeder and Ford, 1983), whereas the coarse sediments represent vadose invasion by proglacial or subglacial streams during deglaciation, and reworking by streams during interglacials. The sequences of sediments within the caves are complex, fragmentary and very difficult to correlate (full details will be published elsewhere). However, sufficient evidence exists to indicate that at least three episodes of subglacial flooding, followed by invasion by high energy streams, have occurred. Additional confirmation is provided by corrosion and abrasion of speleothems, indicating submergence in what are at present dry passages.

Figure 4 indicates that the valley deepening since the Stage A/B diversion is between 140 and 205 m, occurring over three glacial/interglacial cycles since OIS 8. Adopting the shortest time-scale possible, a rough estimate for the average lowering per cycle is 47–68 m. Because it is conceivable that the diversion occurred

earlier, the total lowering might represent four or even five cycles, although there is no positive evidence for this.

DISCUSSION AND CONCLUSION

A rudimentary check on the validity of the model of landscape history presented above can be made by comparing the glacial erosion rates implied here with those determined from process studies. In the case of Allt nan Uamh, some of the valley incision may have been due to fluvial rather than glacial erosion. A formula for the rate of glacial incision which takes this into account is:

$$R_g = 10(L - L_f(1 - g))/g$$

where L is the total incision during a glacial/interglacial cycle, g is the proportion of a cycle for which glaciation occurs, and L_f is the rate of fluvial incision (in metres per cycle). As all estimates of the quantities on the right-hand side have considerable uncertainty attached to them, the most appropriate way to apply the formula is by Monte Carlo simulation. This method requires a probability density function (p.d.f.) to be specified for each independent variable. Random sampling of the p.d.f.s over a large number of trials results in a p.d.f for R_g. Figure 4 shows that the maximum possible value for valley incision is 205 m, and the minimum is indicated as 140 m. An even lower estimate, taking account of valley and possible palaeowater-table slope, is 100 m. An isosceles triangular p.d.f. with upper and lower bounds of 205 and 100 m was used. The value of L depends on total incision and the number of glacial/interglacial cycles. The average length of a cycle was taken to be 10^5 years (Imbrie *et al*., 1984) and separate simulations were performed for three, four and five cycles. These considerations were used to generate appropriately scaled isosceles triangular p.d.f.s for L. For g, a rectangular p.d.f. was used with $0{\cdot}1 \le g \le 0{\cdot}3$, based on Devensian ice-sheet history. A reasonable estimate for the duration of the last ice sheet in Scotland is 10–15 ka (Atkinson *et al*., 1986). Although the existence of an early Devensian glaciation is not certain, the distribution of speleothem dates in Assynt as a whole (Lawson and Atkinson, 1995) implies that its duration cannot have exceeded 10–15 ka. Thus, for a cycle length of 100 ka, a relative total duration of glaciation (g) of $0{\cdot}1 \le g \le 0{\cdot}3$ is reasonable. The p.d.f. for L_f depends upon fluvial incision rates. Comparable studies to this one in fluvial valleys suggest a double rectangular p.d.f. with 56 per cent probability of fluvial incision rates between 50 and 70 mm ka^{-1}, and 44 per cent probability for the range 70–200 mm ka^{-1} (Atkinson and Rowe, 1992; Sasowsky *et al*., 1995; Farrant *et al*., 1995).

Table I summarizes the results of three Monte Carlo simulations with more than 10^5 trials in each. For a three-cycle time-scale there is an 80 per cent probability that R_g lies between 1·53 and 3·75 mm a^{-1}, whereas for five-cycles the 80 per cent probability range is 0·71 to 1·98 mm a^{-1}. Depending on the time-scale, the most probable (i.e. modal) values lie in the range 0·95 to 1·75 mm a^{-1}. Modern process measurements of glacial erosion have been reviewed by Valerie Haynes (personal communication, 1996) and are mainly based on either sediment budget or direct measurement of abrasion at a glacier sole. Results span three orders of magnitude. Our estimates accord with the higher end of the range of sediment budgets (0·06–7 mm a^{-1}) and the lower end of direct abrasion measurements (1–70 mm a^{-1}). This is to be expected as the Allt nan Uamh was a locus of glacial erosion whereas sediment budgets provide areal average values which are probably underestimates because they neglect storage

Table I. Results of Monte Carlo estimation of glacial incision rate (R_g) for comparison with modern process measurements.

No. of glacial/ interglacial cycles	Values of R_g (mm a^{-1})					
	Min.	10 percentile	Mode	Mean (SD)	90 percentile	Max.
3	0·6	1·53	1·75	2·37 (0·87)	3·75	6·3
4	0·3	0·99	1·25	1·68 (0·64)	2·60	4·6
5	0·2	0·71	0·95	1·26 (0·50)	1·98	3·6

effects. Conversely, abrasion measurements tend to be made at points where abrasion is high, and are therefore likely to be biased towards higher values than the average for a glacier as a whole. Estimates of glacial denudation based on large-scale geological data (reviewed by Haynes) are lower than our estimates, which is unsurprising since they are mostly areal averages for whole ice sheets and several glacial/interglacial cycles. Overall, the modern erosion rate estimates agree well with our data. Unfortunately, the spreads of both modern and Monte Carlo values are so great that the comparison sheds little light on whether a time-scale of three, four or five cycles is most likely for the Allt nan Uamh; in the light of the geological and dating evidence we tentatively favour the shortest time-scale of three cycles.

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